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ART. V.—*On the Occurrence of Almandine Garnets in Some Devonian Igneous Rocks of Victoria.*

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Introduction.

Attention was first drawn to the widespread occurrence of pink garnets in the Devonian igneous rocks of Victoria by Dr. N. R. Junner (1), in 1914, but with the few facts at his disposal he preferred not to advance any hypothesis as to their origin.

Investigation has shown that the garnets are characteristic of the rhyodacites, and of certain of the associated porphyries, rhyolites and hypabyssal rocks. No garnet has been observed in any of the hypersthene-dacites (andesites), but at Warburton a small patch of garnet-anthophyllite rock has developed where the hypersthene-dacite has been intruded by granodiorite (2). Garnets of similar character to those in the rhyodacites have also been observed in some of the granodiorites associated with these lavas.

Composition of the Garnets.

Approximate chemical analyses, shown in Table 1, were made of small hand-picked specimens of garnet from several sources. They indicate that the garnets are of relatively similar composition, consisting of almandine, with varying, but minor, proportions of pyrope, andradite, and spessartite.

TABLE 1.—ANALYSES OF GARNETS.

—			1.	2.	3.	4.	5.	6.
			%	%	%	%	%	%
SiO ₂	..	..	34.5	35.0	34.8	34.7	36.4	32.8
Al ₂ O ₃	..	..	23.1	19.8	21.2	18.5	21.4	20.3
FeO*	..	..	39.4	34.2	36.0	36.6	32.1	40.0
MgO	..	..	0.5	5.1	4.8	5.4	7.7	2.4
CaO	..	..	1.9	3.5	1.8	2.7	1.7	1.4
MnO ₂	..	..	1.5	2.3	1.6	2.3	1.5	3.2
TiO ₂	..	..	nil	nil	nil	nil	nil	nil
P ₂ O ₅	..	..	tr.	tr.	tr.	0.5	tr.	0.2
			100.9	99.9	100.2	100.7	100.8	100.3

* FeO = total iron.

1. Garnet from quartz-dacite (rhyodacite) sill, Porphyry Peak, near Mansfield.
2. Garnet from a coarse patch of quartz-biotite-dacite (rhyodacite) near Devil's Elbow, Black's Spur, near Fernshaw.
3. Garnet from quartz-biotite-dacite (rhyodacite), Strathbogie Ranges.
4. Garnet from granodiorite-porphry, dyke or sill, Taggerty.
5. Garnet from granite-porphry or orthoclase-porphry, Mt. Taylor, Eastern Gipsland.
6. Garnet from a contaminated block of granodiorite, Maroonah Dam Tunnel dump, near Donnelly's Weir, Healesville.

Analyst—A. B. EDWARDS.

Garnets in the Rhyodacites

The pink garnets are characteristic of the rhyodacites and such associated rocks as are of relatively similar mineralogical composition, e.g., biotite-rich rhyolites.

The garnets exist either (1) as stable garnets in a state of arrested growth, or (2) as unstable garnets in a state of partial resorption.

(1) STABLE GARNETS.

Stable garnets are typically developed in the quartz-dacite sill, or flow, at Porphyry Peak, near Mansfield. As illustrated in Fig. 1, they occur as somewhat inchoate idiomorphic crystals. The finely crenulated periphery, and the embayments about partially enclosed iron ore grains, which are unable to enter into the composition of their host, indicate that the growth of the garnets was arrested by the crystallization of the lava. Such garnets are invariably surrounded by a rim of partially or completely sericitized felspar, which consists of hypidiomorphic crystals of orthoclase and albite-oligoclase, growing in columnar fashion outwards from the garnet. The width of these felspar rims corresponds more or less to the size of the garnet crystals which they accompany, indicating that it is "reject matter" from the magma and crystalline material out of which the garnet was formed, and that it was thrust outwards by the growing garnet.

A similar feature has been described associated with garnets in the Hooper Mine, United States of America (3). Small quantities of similar felspar accompany the numerous inclusions of iron ore and apatite which are generally present in the garnets.



FIG. 1.—Garnet in a state of arrested growth, showing felspar rim. From rhyodacite of Porphyry Peak. The inclusions consist of iron oxides (black), and epidote and zircon grains (cross hatched). The fracture at the bottom is partially filled with chlorite.

These inclusions represent instances in which “embayments,” referred to above, have been closed round un-assimilated material while the garnet was still growing freely.

So long as the lavas did not undergo differential movements during their period of consolidation, the rims have remained intact, as in the Porphyry Peak sill; but where differential flowage has occurred during the crystallization of the lava, the garnets are frequently shattered, and the rims are often partially torn away.

The garnets in the Porphyry Peak rock contain inclusions of chloritized biotite, iron ore grains, numerous small zircons, and

grains of epidote (?). Identical zircons and epidotes (?) occur throughout the biotite crystals of the rock, and in the groundmass where they may be derived from the breakdown of the biotite phenocrysts which is in progress. The iron ore grains and the epidotes (?) appear to have been precipitated from the biotite during its chloritization. In the garnet they are enclosed in minute areas of potash feldspar, into which a number of zircon crystals are often crowded. Concentrations of zircons and grains of epidote (?) are also found in the feldspar rims, which seems to support the suggestion that these are "reject matter" pushed aside by the growing garnets.

Garnets of this type from other localities are identical, except that the place of the zircon inclusions is frequently taken by apatite, if apatite is the common inclusion of the feldspar or biotite phenocrysts in the rocks which contain the garnets.

In the granite-porphyry of Mt. Taylor (analysed garnet No. 5) large idiomorphic garnets, up to 1 cm. in diameter, occur in the groundmass, while much smaller garnets frequently serve as a nucleus to the large orthoclase phenocrysts which characterize the rock. In this instance the larger garnets and the orthoclase crystals must have crystallized contemporaneously.

(2) UNSTABLE GARNETS.

In some lavas, especially the rhyodacites on the Black's Spur, Marysville, and Strathbogie Ranges (analysed garnets Nos. 2 and 3), the originally idiomorphic garnets are no longer in equilibrium with the magma, and have been preserved in a partially resorbed state. Remnants of a feldspar rim are frequently present. In the Marysville rhyodacites the resorption of the garnets is almost complete, and the final remnants of the garnet are reacting to form biotite (4).

This is also the case at Taggerty (4), where corroded and vermiculate remnants of garnet are observed with clusters of fine biotite flakes about their rims.

In each instance, where there is a clue to the origin of the garnet, either from included minerals or reaction remnants, the garnet appears to have developed from a reaction between previously crystallized ferromagnesian minerals, and either plagioclase crystals or the magma.

At Porphyry Peak the reaction appears to have been—
 magma + plagioclase + biotite \rightarrow garnet + orthoclase + iron ore and albite-oligoclase.

In other instances, as at the Black's Spur (analysed garnet No. 2), the reaction appears to be—

magma + plagioclase + hypersthene \rightarrow garnet + orthoclase and albite-oligoclase.

Granitic Rocks.

GARNETS IN THE GRANODIORITES.

Garnet is a rare mineral in the granodiorites associated with the dacite and rhyodacite lavas, and in granitic rocks in Victoria generally. When it is present it occurs as a reaction product of contamination, generally in association with partially assimilated ferromagnesian-rich xenoliths.



FIG. 2.—Xenolith in granodiorite from Maroondah Dam Tunnel dump. Garnets growing around the rim of the xenolith and in the "strew."

A most instructive specimen was found in the dump from the Maroondah Dam tunnel, near Donnelly's Weir, Healesville (5). The specimen is illustrated in Fig. 2. It is a partially granitized xenolith enclosed in granodiorite. The xenolith consists of two zones:—(1) a core which has been re-crystallized but not granitized, and (2) an outer granitized zone. The core zone consists of micro-porphyroblasts of hypersthene and schillerized poecilitic plates of labradorite, set in a trachytic textured base of plagioclase, quartz and granular pyroxene, and shows an abrupt contact with the granitized zone, in which large porphyroblasts of labradorite have developed, and the hypersthene crystals have been altered completely to biotite. There has been an introduction of quartz which is intergrown with felspar, now greatly calcitized and sericitized. The presence of pyrrhotite and the carbonates points to mineralization during re-crystallization. Portions of this outer zone have been "rafted off" into the magma, becoming disseminated as they floated away from the xenolith.

Numerous pink garnets, as large as 0.5 cm. in diameter, occur in a state of arrested growth at the contact of the outer rim of the granitized zone of the xenolith and the granodiorite, and similar garnets are observed accompanying the clots of biotite which are floating away into the granodiorite (Fig. 2).

These garnets are identical in most respects with the "stable garnets" of the rhyodacites. They have a more irregular outline, and are surrounded by a rim of sericitized feldspar, in which are concentrated numerous crystals of apatite and zircon. Similar apatite and zircons, and rare grains of rutile are included within the garnets, together with small remnants of biotite and small areas of altered feldspar. The apatite and zircon are obviously derived from the feldspar and biotite of the xenolith during their reaction to form garnet. The potash and soda of the biotite and plagioclase has formed the orthoclase and albite of the rim, and this together with many of the not easily assimilated former inclusions has been pushed aside by the growing garnets into a rim. The embayment of the rim of the garnet arises from its inability to assimilate particles of iron ore. Generally it grows round these obstacles, but the onset of crystallization in the rock has preserved the rim in an inchoate state.

A specimen of granodiorite from Braemar House, Macedon, shows a similar development of pink garnet at the contact of a partially assimilated basic clot, consisting of biotite and hypersthene. The garnets carried numerous minute inclusions of iron ore, sometimes associated with feldspar and chloritized remnants of biotite. Similar developments of garnets at the contact of basic inclusions in granitic rocks have been observed at South Morang, and by Tattam (6) at Bulla.

As the garnets become parted from the basic clots by dissemination of the latter through the granite, they lose their stability, and tend to re-dissolve in the magma. This corresponds with the behaviour of the garnets in the rhyodacites.

Garnet in Contact Zones of Dacite and Granodiorite.

In the contact zone of the hypersthene-dacite and granodiorite at Warburton, a small patch of garnet-anthophyllite rock has been found (2), apparently developed from the dacite by recrystallization. The garnet forms lens-shaped poeciloblasts, and appears to have arisen from a reaction between the plagioclase and the anthophyllite or biotite of the rock, since they develop at the contact of plagioclase porphyroblasts and sheaves of anthophyllite. It is somewhat paler in colour than the pink to red garnets of the lavas and granitic rocks, and is probably richer in magnesia. It is so disseminated throughout the rock and so filled with inclusions of anthophyllite that no useful analysis could be obtained.

Products.

ALTERATION OF THE GARNETS.

The garnets in the rhyo-dacites may alter to several distinct minerals:

1. *Alteration to Penninite.*

Most commonly the garnets alter to a bright green penninite, with deep ultra-blue polarisation colours, indicating that it is an iron-rich chlorite. The alteration seems to be almost purely a hydration.

Garnet.

Penninite.



2. *Alteration to Biotite.*

This alteration, which has been observed previously by both Junner (1) and Hills (4), represents a reversal of the process of formation; but whereas in the formation of the garnet there was an excess of ferromagnesian molecules requiring to be saturated with silica, there is now an excess of silica requiring that the available ferromagnesians be more widely shared.

3. *Alteration to Cordierite.*

In several instances Dr. Hills has observed the alteration of garnet to cordierite. As in the formation of secondary biotite, the garnet apparently becomes unstable with the increase of available "free silica," and alters to cordierite, whereby the same amount of ferromagnesian molecules is shared with a larger amount of silica.

Garnet.

Cordierite.



The FeO:MgO ratio must exceed unity for such cordierite, a possibility which has been stressed by Harker (7), who considers that there is probably no limit to the ratio.

This reaction may account for the decrease in the number of garnets and the increase in cordierite trillings as the lavas grow more acid, viz. in the rhyolites and more acid rhyodacites. No cordierite trillings are found in the hypersthene-dacites.

Origin of the Garnets.

Junner (1) was unable to decide whether the garnets were of pyrogenetic origin, or whether they were products of contamination. It is now clear that the garnets in the granitic rocks are products of contamination, derived from the partial assimilation of iron-rich micaceous sediments, such as shales. The garnets of the rhyodacites, however, are too characteristic, numerous, and widespread to be easily explained in this manner, unless the rhyodacites (and their associated lavas) are regarded as syntectics, rather than as true lavas.

Examination of Table 2 shows that the garnets are restricted to those varieties of lava in which quartz occurs as phenocrysts, accompanied by a relatively large amount of ferromagnesian minerals. No garnet has ever been observed in the lavas which have no quartz phenocrysts, e.g., the hypersthene-dacites, felspar porphyrites, and andesites. This association of garnet with quartz phenocrysts indicates that, before the garnet can develop, the magma must have reached a state of "silica saturation" beyond the requirements of the normal ferromagnesian minerals (biotite,

TABLE 2.

Rock.	Garnet.		Phenocrysts.					
			Qz.	Bi.	Hy.	Hb.	Or.	AbAn.
<i>Narbethong—</i>								
Rhyolite	×					×
Quartz-dacite	×	×	×				×
Quartz-biotite-dacite	×	×	×				×
Quar.-bio.-hyp.-dacite	×	×	×	×			×
Granodiorite porphyry	×	×	×				×
Hypersthene-dacite			×	×			×
Andesite				×			×
<i>Marysville—</i>								
Toscanite	×	×	×				×
Nevadite		×					×
Dacite	×	×	×				×
Andesite				×			×
<i>Taggerty—</i>								
Rhyolite	×	×	×				×
Granodiorite porphyry	×	×	×				×
<i>Mansfield—</i>								
Rhyolite	×	×	×				×
Quartz-dacite	×	×	×				×
<i>Dandenong Ranges—</i>								
Toscanite							×
Quartz-dacite	×	×	×				×
Quartz-biotite-dacite	×	×	×				×
Hypersthene-dacite			×	×			×
Hornblende-porphyry					×		×
<i>Warburton—</i>								
Rhyolite		×					×
Quartz-biotite-dacite	×	×	×				×
Hypersthene-dacite			×	×			×
Felspar-porphyrite					×		×
Andesite				×			×
<i>Strathbogie—</i>								
Quar.-bio.-hyp.-dacite	×	×	×	×			×
<i>Mt. Taylor—</i>								
Orthoclase-porphyry	×	×	×				×
<i>Macedon—</i>								
Hypersthene-dacite				×			×

Explanation—

Qz.	=	Quartz.
Bi.	=	Biotite.
Hy.	=	Hypersthene.
Hb.	=	Hornblende.
Or.	=	Orthoclase.
AbAn	=	Plagioclase.

hypersthene or hornblende) and the feldspars. It is also clear that, irrespective of the exact crystal form which they take, the concentration of the crystallized ferromagnesian must exceed a certain minimum. If the proportion of ferromagnesian minerals dwindles below this minimum, the garnets become unstable and dissolve or break down into more stable forms, in which the ferric molecules are shared with a greater number of silica molecules than is possible in garnet. Thus garnets are found only in such rhyolites as possess phenocrysts of ferromagnesian minerals, and, even then, have always entered upon unstable conditions. Similarly, the garnets in the granites are found only in association with local concentrations of ferric material, and become unstable as soon as the ferric concentration is disseminated by further assimilation.

In the hypersthene-dacites the requisite amount of ferromagnesian was present, but there was no "free silica," and hence no garnet. Where, however, such a hypersthene-dacite has been recrystallized by granodiorite under favorable conditions, probably determined by a combination of pressure and temperature, garnet has formed, the quartz of the groundmass, which was not available in the lava state, providing the "free silica."

The development of garnet, therefore, marks a distinct stage in the crystallization differentiation of these lavas—a stage characterized by the development of "free silica" in the magma, and the retention of a certain concentration of crystallized ferromagnesian minerals. The maximum concentration of garnet occurs when about 50 per cent. of the magma has crystallized, as indicated by the following micrometric analyses:—

				1.	2.	3.
				%	%	%
<i>Phenocrysts —</i>						
Quartz..	..	..	..	13.2	11.5	15.5
Biotite, &c.	..	..	..	10.5	15.5	10.5
Feldspars	..	..	..	28.9	27.0	18.3
<i>Groundmass</i>	..	..	..	47.4	46.0	55.7

1. Rhyodacite (or quartz-hypersthene-biotite-dacite), Bladin's Quarry, top of Black's Spur.

2. Rhyodacite (or quartz-biotite-dacite), midway up the Black's Spur.

3. Rhyodacite (or quartz-dacite) from Porphyry Peak, near Mansfield.

As crystallization advances with further magmatic cooling, the ratio of Free Silica to Ferromagnesian increases, and the garnets become unstable. Accordingly, in acid plutonic rocks, granites and granodiorites, garnet is an exceptional mineral. The garnet is only preserved if extrusion occurs to "freeze" the magma before further crystallization takes place.

Viewed in this light, the garnet appears to be a true "discontinuous reaction" mineral (8), but it also tends to be "syntectic" (9), developing mainly from interaction between previously crystallized minerals. The effect of assimilation would only hurry the process if it introduced silica to the magma, or prolong it if it introduced ferromagnesians. The rhyolites, the various rhyodacites, and the hypersthene-dacites have all assimilated Silurian shales and sandstones, but garnets are absent from the hypersthene-dacites, and, commonly, from the rhyolites. Moreover, as the rhyodacites become more acid, the amount of garnet in them correspondingly decreases. Assimilation of similar sediments to at least equal degree in the granodiorites and granites has only served to prolong the garnetiferous stage sporadically in them.

If, as indicated, the garnets are pyrogenetic, then garnetiferous rhyodacites should be a frequent (and characteristic?) feature of andesite-rhyolite suites; and in this respect it may be noted that the development of almandine garnets in rocks of this type is not uncommon. The author has observed them in specimens of relatively similar dacitic types from New Zealand, Italy, and Hungary, and Iddings (10) refers to almandine garnet as occurring in granites and some andesites.

The development of garnets in such lavas obviously occurs at a late stage in the cooling history of the magma, and previous to extrusion. Frequently it is brought to a close by the sudden increase of viscosity accompanying extrusion. It is often later than, or accompanied by, such deuteric phenomena as chloritization of biotite or hornblende, and the introduction of sulphide minerals; and where there has been a concentration of mineralisers, as in some pockets of coarser rock in the Black's Spur rhyo-dacite, the reduced viscosity of the magma has permitted the garnets to become more numerous and larger than usual.

Summary.

Almandine garnets of pyrogenetic origin are characteristic of the Upper Devonian rhyodacites of Victoria, and some associated rhyolites and hypabyssal rocks. They developed at a late period in the cooling of the lavas, at a stage when the ferromagnesians were still fairly concentrated, but silica was crystallizing in excess of the needs of both ferromagnesians and feldspars. With diminution of the ferric content of the lavas they become unstable and re-dissolved.

Similar garnets occur sporadically in associated granitic rocks, in association with partially assimilated basic clots. With dissemination of the basic clots these garnets also become unstable.

The unstable garnets may merely dissolve, or they may alter to penninite, secondary biotite, or to iron-rich cordierite.

Similar garnetiferous rhyodacites should characterize other andesite-rhyolite suites.

Acknowledgments.

In conclusion, I wish to thank the staff of the Geology Department and the Curator of the Geological Survey Museum for help in obtaining specimens for analysis, and Professor Skeats for permission to make the analyses in the departmental laboratory.

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